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REPORT NO. NADC-85112-60

EFFECTIVENESS OF FATIGUE LIFE ENHANCING FASTENERS IN THE DESIGN AND REWORK OF AIRCRAFT STRUCTURES

AD-A159 676

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FEBRUARY 1985

FINAL REPORT
Period Covering February 1982 to February 1985
AIRTASK NO. WF41-40000
Program Element No. 62241N
Work Unit No. ZA650

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Prepared for
NAVAL AIR SYSTEMS COMMAND
Department of the Navy
Washington, DC 20361

85 10 02 011

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b RESTRICTIVE MARKINGS N/A
2a SECURITY CLASSIFICATION AUTHORITY N/A 2b DECLASSIFICATION/DOWNGRADING SCHEDULE N/A	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for Public Release; Distribution is Unlimited.
4 PERFORMING ORGANIZATION REPORT NUMBER(S) NADC-85112-60	5 MONITORING ORGANIZATION REPORT NUMBER(S) N/A
6a NAME OF PERFORMING ORGANIZATION Aircraft and Crew Systems Technology Directorate 6b OFFICE SYMBOL (If applicable) 6043	7a NAME OF MONITORING ORGANIZATION N/A
6c ADDRESS (City, State, and ZIP Code) Naval Air Development Center Warminster, PA 18974-5000	7b. ADDRESS (City, State, and ZIP Code) N/A
8a NAME OF FUNDING/SPONSORING ORGANIZATION Naval Air Systems Command 8b OFFICE SYMBOL (If applicable) N/A	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N/A
8c ADDRESS (City, State, and ZIP Code) Department of the Navy Washington, DC 20361	10 SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO: 62241N PROJECT NO: N/A TASK NO: WF41-40000 WORK UNIT ACCESSION NO: ZA650

11 TITLE (Include Security Classification)

(U) Effectiveness of Fatigue Life Enhancing Fasteners In The Design And Rework Of Aircraft Structures

12 PERSONAL AUTHOR(S) P. A. Kozel

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Final	FROM 2/82 TO 2/85	1985, February 28	22

16 SUPPLEMENTARY NOTATION

17 COSATI CODES		
FIELD	GROUP	SUB-GROUP

18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

Fatigue, Crack-Growth, Fasteners, Structural Rework, ~~Fatigue Life Enhancing~~ Joints.

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

Fatigue life data were obtained for four different types of fatigue life enhancing (FLE) fasteners installed in new uncracked holes and in reworked, pre-cracked holes. The first condition represented a new design where the FLE fasteners are installed during production. The second condition represented a structural rework in which fastener holes are reamed to a larger size to remove fatigue or fretting damage but might still contain a small undetected crack.

Results showed that the FLE fasteners produced approximately the same overall fatigue life in the new design and the rework condition and provided a significant increase in life compared to conventional non-FLE fasteners.

Tests were performed with 7075-T6 aluminum alloy under spectrum loading typical of a Navy fighter/attack type of aircraft. For the rework condition, the pre-crack size was limited to .03 inch (.76mm). Flush head fasteners were used in all tests. Keywords

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a NAME OF RESPONSIBLE INDIVIDUAL P.A. Kozel	22b TELEPHONE (Include Area Code) 215-441-1608 22c. OFFICE SYMBOL 6043

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted

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SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

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FOREWORD

This program was performed in the Structures Research and Development Branch, Aero Structures Division, Aircraft and Crew Systems Technology Directorate, of the Naval Air Development Center. Mr. Paul Kozel was the project engineer and author of the report. Mr. E. Valdez and Mr. H. Slavin conducted the fatigue tests.

The author wishes to thank Dr. Basil Leftheris of the Grumman Aerospace Corporation and Mr. Robert Champoux of Fatigue Technology Incorporated for the support which they provided during this program.

SUMMARY

Fatigue life data were obtained for four different types of fatigue life enhancing (FLE) fasteners installed in new uncracked holes and in reworked, pre-cracked holes. The first condition represented a new design where the FLE fasteners are installed during production. The second condition represented a structural rework case in which fastener holes are reamed to a larger size to remove fatigue or fretting damage but might still contain a small undetected crack.

Results showed that the FLE fasteners produced approximately the same overall fatigue life in the new design and the rework condition and provided a significant increase in life compared to conventional non-FLE fasteners.

Tests were performed with 7075-T6 aluminum alloy under spectrum loading typical of a Navy fighter/attack type of aircraft. For the rework condition, the pre-crack size was limited to .03 inch (.76mm). Flush head fasteners were used in all tests.

SECTION 1.0

INTRODUCTION

Fatigue life enhancing (FLE) fasteners are now widely accepted in aircraft structures applications because of their demonstrated capability to delay crack initiation and inhibit crack growth. Because of their higher cost, their utilization is usually limited, in new design, to local areas shown by test or analysis to be fatigue sensitive, or else they are reserved for later rework in service life extension programs or as a curative for unforeseen fatigue problems which occur in service.

The intent of this program was to provide some insight into the comparative performance of typical FLE fastener systems under new design and rework conditions. For the new design, or production case, the fasteners were installed in test coupons made of new material with clean, uncracked holes. For the rework, life extension case, the coupons were pre-fatigued with baseline non-FLE fasteners installed and then reworked for the next larger diameter fastener. Small cracks were introduced after hole rework but prior to installing FLE fasteners. The cracks were introduced on the premise that some fastener holes, even after rework and NDI, could contain small undetected cracks and that the period of safe life extension would depend on how effective the FLE fastener systems were in inhibiting subsequent crack growth.

Overall life comparisons between the two cases would help define the best usage philosophy for FLE fastener systems in aircraft structures, i.e., whether to use them more extensively in the production airframe at higher initial cost or to restrict their use to local areas of high fatigue susceptibility and defer any additional use until a specific need arises from a service problem or life extension requirement.

SECTION 2.0

TEST PROGRAM AND PROCEDURES

2.1 TEST PLAN

The test program was performed in two phases. Phase I represented a new design condition with tests of .19 in. (4.8mm) dia. fasteners installed in new material. Phase II represented a severe case rework condition where test coupons were pre-fatigued under spectrum loading to the equivalent of 3000 hours of operational usage, reworked for .25 in. (6.4mm) dia. fasteners, and pre-cracked prior to fastener installation. Three replicate coupons were tested for each fastener type in each Phase. Each coupon had three countersunk fasteners. The overall test matrix is shown in Table 1.

TABLE 1. TEST MATRIX

Fastener System	Phase I New Design - 3/16" Dia. Fasteners	Phase II Rework - 1/4" Dia. Fasteners
Straight Shank - Clearance Fit	✓	
Tapered Shank - Interference Fit	✓	✓
Straight Shank - Interference Fit	✓	✓
Dynamically Formed Rivet	✓	✓
Sleeve Cold-Worked Hole[1]	✓	✓
Sleeve Cold-Worked Hole[2]		✓

Notes: 1. Correct process: cold worked prior to countersinking
2. Incorrect process: cold worked after countersinking

2.2 TEST SPECIMEN DESIGN

For reasons of simplicity and cost, the simple dogbone, zero load transfer coupon shown in Figure 1 was chosen for the fatigue test program. Since edge distance effects were considered important, the fasteners were installed off-center with an edge distance typical of aircraft design practice. The test specimen could sustain the spectrum compression loads without anti-buckling guides. All test specimens were fabricated from the same sheet of 7075-T6 aluminum alloy and used steel fasteners. The basic properties of the aluminum sheet, as determined from tensile coupons, are given in Table 2.

TABLE 2. MATERIAL PROPERTIES

7075-T6 ALUMINUM ALLOY

F_{TU}	F_{TY}	E
82800 psi (571 MPa)	78900 psi (544 MPa)	10.37×10^6 psi (71.5×10^9 MPa)

- o Tensile tests per ASTM method E-8
- o Values based on average of 3 coupons
- o F_{TY} values based on 0.2% offset

2.3 FASTENER TYPES:

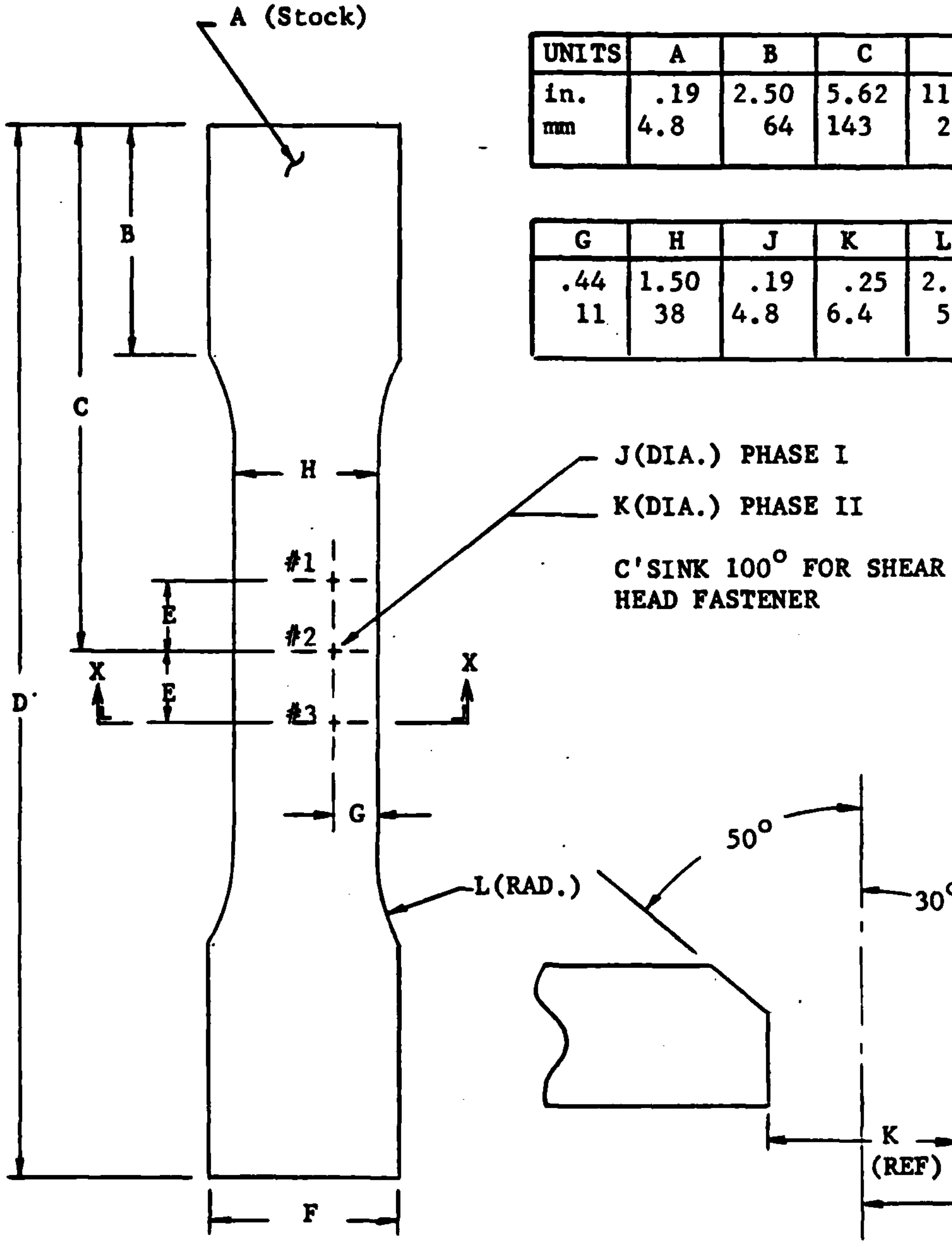
The following fastener systems were tested

- o Straight shank interference-fit
- o Tapered shank interference-fit
- o Sleeve cold worked holes with clearance fit fasteners
- o Dynamically formed A-286 alloy rivets
- o Standard clearance-fit fasteners

The standard clearance-fit fasteners are not considered fatigue life enhancing and provided a baseline from which to assess the other systems.

UNITS	A	B	C	D	E	F
in.	.19	2.50	5.62	11.25	.75	2.00
mm	4.8	64	143	286	19	51

G	H	J	K	L	M	N
.44	1.50	.19	.25	2.00	.03	.02
11	38	4.8	6.4	51	.76	.51



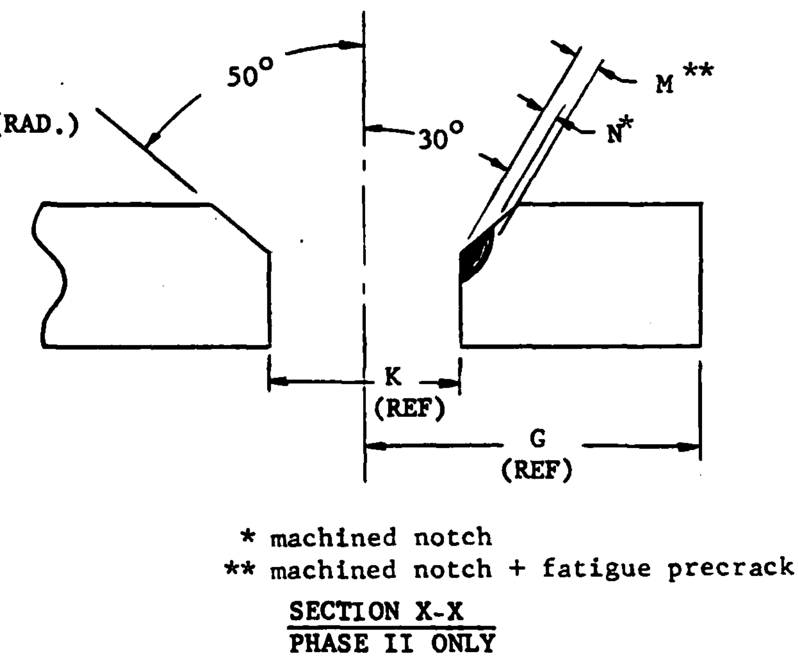


FIGURE 1. FATIGUE TEST SPECIMEN

All fasteners were steel alloy of the 100° flush shear head configuration. Fasteners of .19 in. diameter were used for the condition representing new design and .25 in. dia. fasteners were used for the rework condition. Both sizes were installed with identical edge distance of .44 in. (11mm).

Straight and tapered shank fasteners were installed within manufacturer recommended diametral interference limits of .002 to .004 inch for both the .19 in. and .25 in. diameters. Manufacturer supplied tooling was used for the tapered shank fasteners and typically produced interferences in the low to mid range (i.e., .002 to .003 inch). The straight shank interference fits were then produced with interferences in this same range. Sleeve cold worked holes were also processed with the manufacturer's tooling and according to his specifications. The tooling supplied for cold working was closer to the high side of the manufacturer's specified tolerance band and produced diametral expansions of approximately .0125 inch or 5%. Dynamically formed rivets were installed per manufacturer's specifications on special riveting equipment designed to produce the optimum fatigue improvement. No simple measurand, such as interference, is available to characterize the rivet installation. Fasteners in cold worked holes were installed with .0005 $\pm$ .0005 inch diametral clearance. Fasteners in the baseline clearance-fit condition were installed with diametral clearance of .001 in. to .005 in. All interference-fit fasteners were supplied with a dry film lubricant. All other fasteners were lubricated with cetyl alcohol except for the rivets which were not lubricated.

To minimize clampup effects, nuts were installed with minimum run-on torque in all cases. This required that interference-fit fasteners be pressed into holes rather than being drawn in by the nut.

2.4 PRE-CRACKING PROCEDURE

For tests representing a reworked hole containing a small crack, the .25 in. dia. fastener holes were pre-cracked as follows.

1. Test specimens were made with .19 in. dia. standard fasteners and fatigue tested under spectrum loading to 3,000 equivalent flight hours.
2. Holes were opened to the proper rework diameter (nominally .25 in.) and countersunk.
3. A sharp notch was machined into the fastener hole as shown in Figure 1 and sharpened by fatigue cycling of an additional 600 equivalent flight hours of the test spectrum.

This produced a corner crack at the countersink-to-hole intersection of approximately .03 in. of total depth with a natural crack front shape and acuity.

The sleeve cold worked holes were an exception. In this case, the notching and cold working were done prior to the final countersink operation. According to the manufacturer of the cold work system, a loss of fatigue life will occur if countersinking is done prior to cold working. Coupons with incorrect processing were also tested and, as shown in the basic test data (Table A1), did exhibit significant loss of fatigue life. Improper installation of any of the FLE systems will cause serious loss of fatigue life.

2.5 TEST LOADS AND CONDITIONS

The test spectrum was based on a design spectrum representing the equivalent of 6000 flight hours of operational usage for a modern Navy fighter/attack aircraft. It contained positive (tension) and negative (compression) cyclic loads of variable range and mean. The baseline spectrum was simplified to reduce test time and to suit the capability of the test machine programming equipment. Simplification consisted of elimination of small magnitude cycles, which analysis showed would produce little damage, and a reordering into small fixed sequence blocks. The simplified spectrum consisted of four blocks, each representing 50 equivalent flight hours (EFH), repeated to failure. Loads within each block were arranged in lo-to-hi order with respect to peak and range. The detailed load spectrum and sequence is given in Table A3. Spectrum content for 200 EFH is shown in matrix form in Table 3 below.

TABLE 3. TEST SPECTRUM LOAD MATRIX

Number of cycles for 200 EFH

MAXIMUM LOAD LEVEL

1.000			1					
.913		9	9					9
.826			9	9			9	
.739			16	9			9	9
.652		27	27	27	9			
.565	9	63	36	27	27	9		
.478		162	63	72	36	9		
.391		99	315	225	9			
.304	18	162	450	144				
.217	9	81	45					
.130	9	18						
.043	6	3						
	-.130	-.043	.043	.130	.217	.304	.391	.478

MINIMUM LOAD LEVEL

Load levels are given as ratios of maximum test load. Test load corresponding to spectrum load level of 1.000 is 12,000 lbs. (53,378N).

The maximum spectrum load (corresponding to a peak value of 1.0 in Table A3) was 12,000 pounds (53,378N) which produced a specimen gross section stress of 42,105 psi (290 MPa). This stress level was selected to produce test lives in the Phase I baseline specimens of approximately 12,000 EFH which is the typical fatigue test requirement for a Navy fighter aircraft with a specified design life of 6,000 flight hours.

Both Phase I and Phase II tests were performed at the same spectrum load level. In Phase II, with .25 in. dia. fasteners, the slightly higher net section stress was compensated somewhat by a lower net section stress concentration factor[8] producing a slightly higher (less than 1%) elastic stress condition at the hole edge nearest to the narrow ligament of the test specimen. However, these geometric stress concentration factors are for open holes, and all tests were performed with fasteners in the holes.

All tests were performed in MTS electro-hydraulic, closed loop servo controlled test machines in a laboratory environment nominally maintained at 75°F and 45% relative humidity.

SECTION 3.0

RESULTS AND DISCUSSION

Test results are plotted in Figure 2. Sample mean lives were obtained from a linear regression fit to an assumed log-normal distribution. The 90% confidence limits were also calculated from the sample standard deviation obtained from the regression analysis. The log-normal distribution was chosen over the Weibull based on goodness of fit tests done in reference 2 for a similar test program with a larger sample size. Choice of distribution would not affect the general comparisons made here. The basic test data is presented in Appendix A.

From Figure 2, the most significant result is that the FLE fastener systems produced essentially the same overall life for the new design (uncracked holes) condition of Phase I and for the rework (holes with .03 in. cracks) condition of Phase II. If all the FLE fastener data in each phase is assumed to be from the same population, Figure 2 shows that the mean life in each phase is very nearly the same. This is especially true if an increment of 6000 EFH is added to the Phase II test lives to represent the crack initiation life and crack growth life to the .03 in. initial crack size. Based on the life-to-first-crack data, also shown in Figure 2, a 6000 EFH increment is not an unreasonable choice.

The conclusion that the FLE systems can produce the same overall life for both cracked and uncracked holes is limited to the case of small cracks. How small is small is difficult to define in general terms, but

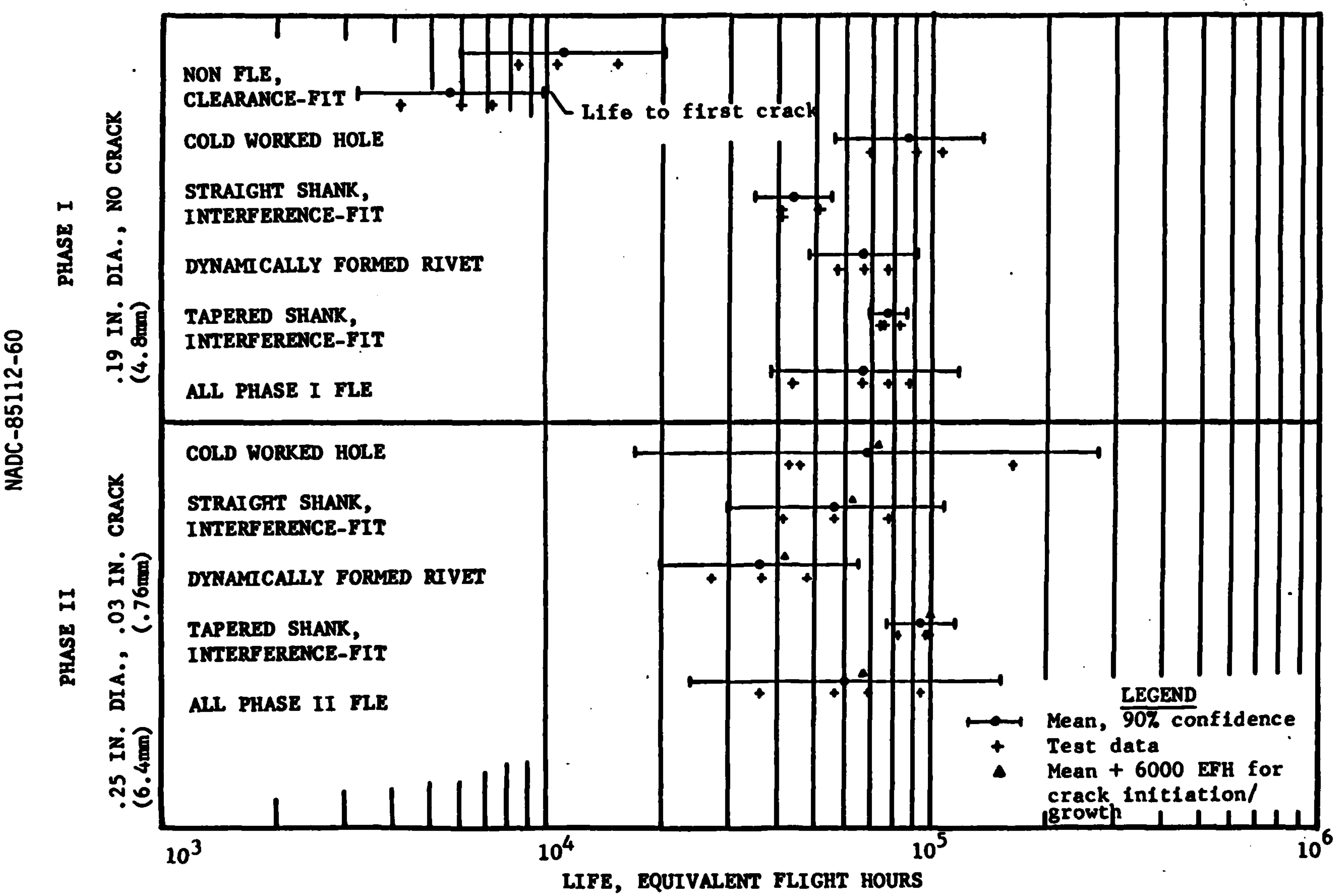


FIGURE 2. FATIGUE LIFE COMPARISONS

other investigators[4,5] have shown that the ability of some of these fastener systems to retard crack growth degrades appreciably when the crack length exceeds about .08 inch in .19 or .25 inch diameter holes. This implies that the rework application carries some additional risk if cracks of this size go undetected in post-rework NDI.

Another observation from Figure 2 is that the data dispersion is generally larger for the Phase II tests. This resulted in a larger standard deviation and hence much wider confidence limits on the sample means. Log-normal cumulative distribution functions, where all the FLE fastener data in each phase is assumed to belong to the same population, are plotted in Figure 3. The slope difference illustrates the difference in overall standard deviation between Phase I and Phase II. Whether this is caused by small variations in the initial crack size in Phase II or by some effect of the crack on the FLE stress field is speculative, but the former explanation is credible since small cracks are difficult to introduce with precision. Rankings of the different FLE systems cannot be asserted with any statistical authority based on these tests. The typical high dispersion of the fatigue test data and the small sample size result in overlapping confidence intervals which make rankings based on mean test life inconclusive. Rankings based on mean test life also change from Phase I to Phase II. From Figure 2, it can be observed that the cold worked hole and the tapered shank systems were the best performers based on mean life and that the dispersion of the tapered shank data was remarkably small. However, this result is not consistently seen in other investigations[2,3,4,5] published in the literature. Moreover, the aforementioned references also show that process variations (interference level, amount of radial deformation, etc.) even within the tolerances recommended by the manufacturers of the various systems

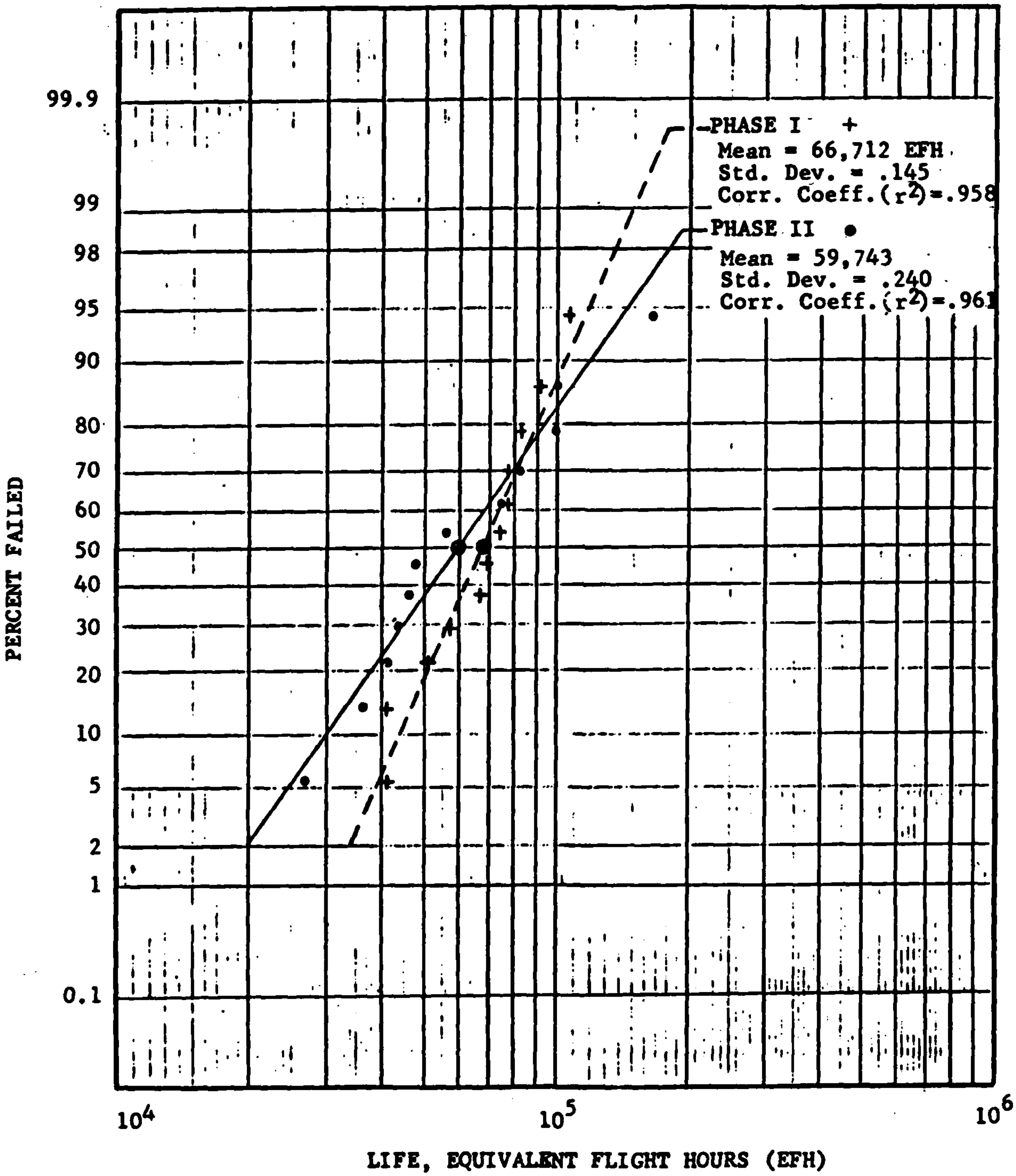


FIGURE 3. COMPARISON OF PHASE I AND PHASE II CUMULATIVE DISTRIBUTION FUNCTIONS

produce fatigue life variations which can overshadow any performance differences which might exist between systems.

Given the equivalence of performance of FLE fasteners under new production or rework conditions, the designer faces the traditional choice between design philosophies:

1. Invest in more extensive FLE fastener use in production to improve airframe reliability, reduce life cycle costs, and possibly preclude a later rework, or

2. Opt for lower production cost with minimum use of the more expensive FLE fasteners with some increased risk of in-service problems requiring rework and aircraft down time.

Of course, judicious design blurs the distinction between these two choices, nevertheless, the development of lower cost FLE fasteners and automated production processes would make wider use of FLE fasteners in design more cost effective and add significantly to airframe durability with an accompanying reduction in life cycle costs.

SECTION 4.0

CONCLUSIONS AND RECOMMENDATIONS

1. Based on the data from this investigation, fatigue life enhancing (FLE) fasteners produce essentially the same overall life whether used for new design in clean, uncracked holes or for later structural rework in holes containing small residual cracks.

2. The data does not support conclusions favoring any single FLE fastener system over any other. However, the FLE systems do produce a significant life increase over conventional non-FLE fasteners.

3. Long term economic and operational considerations favor more extensive use of FLE fasteners in new aircraft production, but their higher initial cost is a deterrant in the typical competitive environment of a new aircraft buy. The development of low cost FLE systems and/or automated manufacturing processes would lower production costs and promote more extensive use of these fasteners. Potential user benefits, such as extended airframe service life and lower life cycle costs recommend a Manufacturing Technology (MNT) program to support this development.

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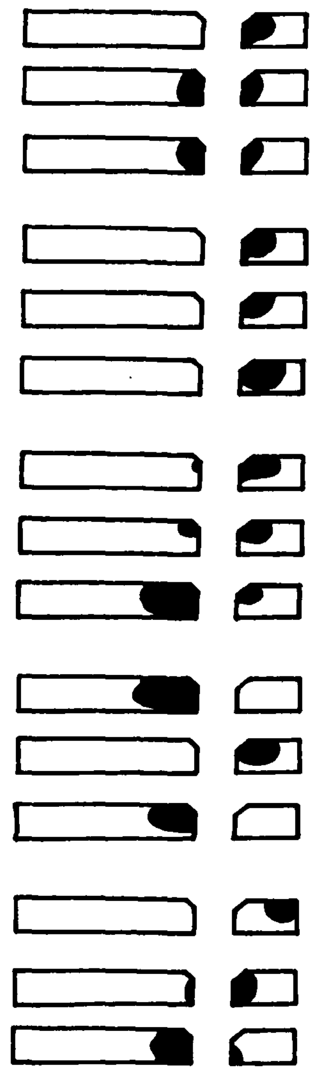
APPENDIX A

TABLE A1. BASIC TEST DATA

PHASE I, 3/16 INCH DIAMETER, NO CRACKS

FASTENER TYPE	SPECIMEN NO.	LIFE TO FAILURE[1]	LIFE TO FIRST CRACK[1]	FAILURE SKETCH[2] & LOCATION[3]
Straight Shank.	R12	10600	7200	3
Clearance-Fit	K2	8400	4200	3
	P2	15200	6000	1
Tapered Shank,	C2	74200		3
Interference-Fit	J2	82400		3
	L11	75800		2
Straight Shank,	J12	40800		3
Interference-Fit	F3	51000		2
	P11	40800		2
Dynamically	E3	66800		2
Formed Rivet	G7	57000		1
	M7	77300		2
Sleeve Cold-	H1	69000		1
Worked Hole	C12	91400		1
	P1	106400		3

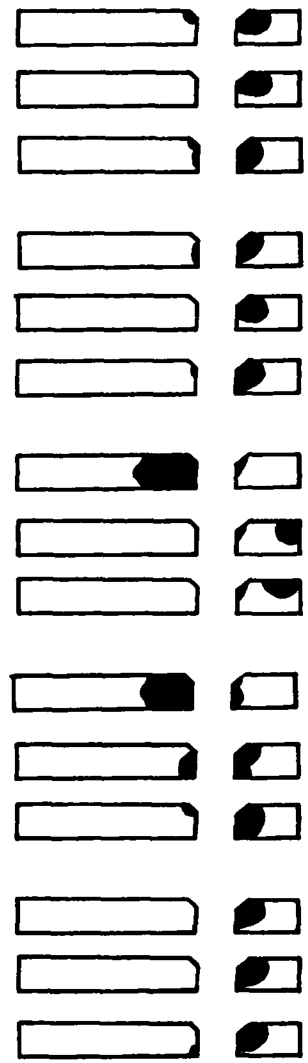


Notes:
1. In equivalent flight hours
2. Dark areas delineate boundary of fatigue striations
3. Location given by hole number, see Figure 1.

TABLE A2. BASIC TEST DATA

PHASE II, 1/4 INCH DIAMETER, .03 INCH CRACK

FASTENER TYPE	SPECIMEN NO.	LIFE TO FAILURE[1]	FAILURE SKETCH[2] & LOCATION[3]
Tapered Shank,	S31	99600	3
Interference-Fit	L32	99400	1
	Q33	81800	1
Straight Shank	J3	55600	3
Interference-Fit	S2	76800	2
	B7	41000	3
Dynamically	A2	36000	2
Formed Rivet	A11	47200	3
	H12	26600	2
Sleeve Cold-	35	164600	3
Worked Hole	36	45800	1
	37	42800	1
Sleeve Cold-	H11	24400[4]	2
Worked Hole	N2	18400[4]	3
	D11	13000[4]	3



Notes:
1. In equivalent flight hours
2. Dark areas delineate boundary of fatigue striations
3. Location given by hole number, see Figure 1.
4. Incorrect process, countersunk prior to cold work

TABLE A3. TEST SPECTRUM

Max. Load Level [1]	Min. Load Level [1]	N	
0.043	-0.130	2	
0.130	-0.043	5	
0.130	-0.130	2	
0.217	0.043	11	
0.217	-0.043	20	
0.217	-0.130	2	
0.304	0.130	36	
0.304	0.043	113	
0.304	-0.043	41	
0.304	-0.130	5	
0.391	0.217	2	
0.391	0.130	56	
0.391	0.043	79	
0.391	-0.043	25	
0.478	0.304	2	
0.478	0.217	9	
0.478	0.130	18	Block I 50 EFH
0.478	0.043	16	
0.478	-0.043	41	
0.565	0.304	2	
0.565	0.217	7	
0.565	0.130	7	
0.565	0.043	9	
0.565	-0.043	16	
0.565	-0.130	2	
0.652	0.217	2	
0.652	0.130	7	
0.652	0.043	7	
0.652	-0.043	7	
0.739	0.478	2	
0.739	0.391	2	
0.739	0.130	2	
0.739	0.043	4	
0.826	0.391	2	
0.826	0.130	2	
0.826	0.043	2	
0.913	0.478	2	
0.913	0.043	2	
0.913	-0.043	2	
0.043	-0.130	2	
0.130	-0.043	4	
0.130	-0.130	2	
0.217	0.043	11	
0.217	-0.043	20	
0.217	-0.130	2	
0.304	0.130	36	
0.304	0.043	112	
0.304	-0.043	40	
0.304	-0.130	4	
0.391	0.217	2	

TABLE A3. TEST SPECTRUM (continued)

Max. Load Level [1]	Min. Load Level [1]	N	
0.391	0.130	56	
0.391	0.043	79	
0.391	-0.043	25	
0.478	0.304	2	
0.478	0.217	9	
0.478	0.130	18	
0.478	0.043	16	
0.478	-0.043	40	
0.565	0.304	2	
0.565	0.217	7	
0.565	0.130	7	Block II
0.565	0.043	9	50 EFH
0.565	-0.043	16	
0.565	-0.130	2	
0.652	0.217	2	
0.652	0.130	7	
0.652	0.043	7	
0.652	-0.043	7	
0.739	0.478	2	
0.739	0.391	2	
0.739	0.130	2	
0.739	0.043	4	
0.826	0.391	2	
0.826	0.130	2	
0.826	0.043	2	
0.913	0.478	2	
0.913	0.043	2	
0.913	-0.043	2	
0.043	-0.130	2	
0.130	-0.043	5	
0.130	-0.130	2	
0.217	0.043	11	
0.217	-0.043	20	
0.217	-0.130	2	
0.304	0.130	36	
0.304	0.043	113	
0.304	-0.043	41	
0.304	-0.130	5	Block III
0.391	0.217	2	50 EFH
0.391	0.130	56	
0.391	0.043	79	
0.391	-0.043	25	
0.478	0.304	2	
0.478	0.217	9	
0.478	0.130	18	
0.478	0.043	16	
0.478	-0.043	41	
0.565	0.304	2	
0.565	0.217	7	
0.565	0.130	7	

TABLE A3. TEST SPECTRUM (continued)

Max. Load Level [1]	Min. Load Level [1]	N	
0.565	0.043	9	
0.565	-0.043	16	
0.565	-0.130	2	
0.652	0.217	2	
0.652	0.130	7	
0.652	0.043	7	
0.652	-0.043	7	
0.739	0.478	2	
0.739	0.391	2	
0.739	0.130	2	
0.739	0.043	4	
0.826	0.391	2	
0.826	0.130	2	
0.826	0.043	2	
0.913	0.478	2	
0.913	0.043	2	
0.913	-0.043	2	
0.043	-0.043	3	
0.130	-0.043	4	
0.130	-0.130	3	
0.217	0.043	12	
0.217	-0.043	21	
0.217	-0.130	3	
0.304	0.130	36	
0.304	0.043	112	
0.304	-0.043	40	
0.304	-0.130	4	
0.391	0.217	3	
0.391	0.130	57	
0.391	0.043	78	Block IV
0.391	-0.043	24	50 EFH
0.478	0.304	3	
0.478	0.217	9	
0.478	0.130	18	
0.478	0.043	15	
0.478	-0.043	40	
0.565	0.304	3	
0.565	0.217	6	
0.565	0.130	6	
0.565	0.043	9	
0.565	-0.043	15	
0.565	-0.130	3	
0.652	0.217	3	
0.652	0.130	6	
0.652	0.043	6	
0.652	-0.043	6	
0.739	0.478	3	
0.739	0.391	3	
0.739	0.130	3	
0.739	0.043	4	

TABLE A3. TEST SPECTRUM (continued)

Max. Load Level [1]	Min. Load Level [1]	N
0.826	0.391	3
0.826	0.130	3
0.826	0.043	3
0.913	0.478	3
0.913	0.043	3
0.913	-0.043	3
1.000	0.043	1

[1] Load levels are given as ratios of maximum test load. Test load corresponding to maximum spectrum load level of 1.000 was 12,000 lbs. (53,378N)

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